

Constraining neutrino superluminality from searches for sterile neutrino decays

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Abstract

Superluminal neutrinos are expected to lose energy due to bremsstrahlung. It is dominated by e^+e^- -pair production if kinematically allowed. The same signature was used in searches for 3-body decays of hypothetical heavy sterile neutrinos. From the published analyses of these searches performed by CERN PS191 and CHARM experiments we set upper limits on the neutrino velocity in the energy range from 0.2 GeV to 280 GeV. Our limits are well below the neutrino velocity favored by the recent OPERA results. For energy-independent neutrino velocity the limits obtained in this paper are stronger than those coming from ICARUS experiment and observations of Supernova SN1987a.

Recently neutrino physics has attracted renewed attention because of the surprising result of the OPERA collaboration [1] (see, however [2]). Their claim is that the travel time of muon neutrino ν_μ with average energy 17.5 GeV is smaller than the light travel time at the confidence level above 5σ . This result was interpreted as a superluminal propagation of muon neutrino, which can be parametrized by

$$\delta \equiv (v_\nu^2 - 1) \simeq 5 \times 10^{-5} , \quad (1)$$

where v_ν is the neutrino velocity and we set the Planck constant \hbar and photon velocity c equal to unity, $\hbar = c = 1$.

However, Cohen and Glashow [3] put forward a serious objection to this superluminal interpretation. They considered several decay processes which would take place in vacuum

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under the assumption $\delta > 0$. It was pointed out that by analogy to the Cherenkov radiation, the electroweak process

$$\nu_\mu \rightarrow \nu_\mu + e^+ + e^- \quad (2)$$

should occur, and the neutrino spectrum should be drastically changed as neutrinos travel a distance of about 730 km from the target at CERN to the OPERA detector at Gran Sasso. The neutrino energy spectrum near the OPERA detector was measured by the ICARUS collaboration, and no attenuation was observed. Using the result of Cohen and Glashow [3] and the analysis of the ICARUS data, the limit

$$\delta < 4 \times 10^{-8} \quad (3)$$

was obtained [4] under the assumption of energy-independent δ .

In this paper we give interpretation of other neutrino experiments, where the emission of e^+e^- -pair could be observed, in terms of the decay (2). The rate of the decay (2) in the laboratory frame is given by

$$\Gamma = k' \frac{G_F^2}{192 \pi^3} E^5 \delta^3, \quad (4)$$

where G_F is the Fermi constant, E is the neutrino energy and k' is a numerical constant. In the original paper [3] the value $k' = 1/14$ was used for estimates. As shown in Ref. [5], this value is model-dependent and can be made two or three times smaller. Due to the very strong dependence of (4) on δ and neutrino energy the precise value of k' is not crucial for our estimates and we adopt $k' = 1/14$, which was also accepted in Ref. [4] when obtaining the upper bound (3). The threshold of the pair production (2) is

$$E = 2m_e/\sqrt{\delta}. \quad (5)$$

The signature of the process (2) is the appearance of e^+e^- -pair from nothing downstream of a neutrino beam. Remarkably, the same signature is exploited in searches for heavy sterile neutrino decays. Indeed, sterile neutrinos mix with the Standard Model (SM) active neutrinos thereby producing masses and mixing in active neutrino sector required to explain the neutrino oscillations. This mixing also gives rise to sterile neutrino production in meson decays and subsequent sterile neutrino decays into SM particles including $e^+e^-\nu$, i.e. the same final state as in (2) (for a concrete model example see, e.g., Ref. [6]).

In the neutrino energy range $E \sim 1\text{--}8\text{ GeV}$ the stringent bound on the lepton pair production follows from the analysis of CERN PS191 experiment. Neutrinos were eventually produced on a beryllium target by protons of energy 19 GeV. This experiment was specially designed [7] to look for possible sterile neutrino decays to $e^+e^-\nu$ in vacuum and has observed

no events with collected statistics of 8.6×10^{18} protons on target. The differential energy spectrum of muon neutrinos dN_ν/dE expected from Monte Carlo simulations in the range of energies from 200 MeV to 8 GeV is presented in Ref. [8] and shown in Fig. 1. In the case

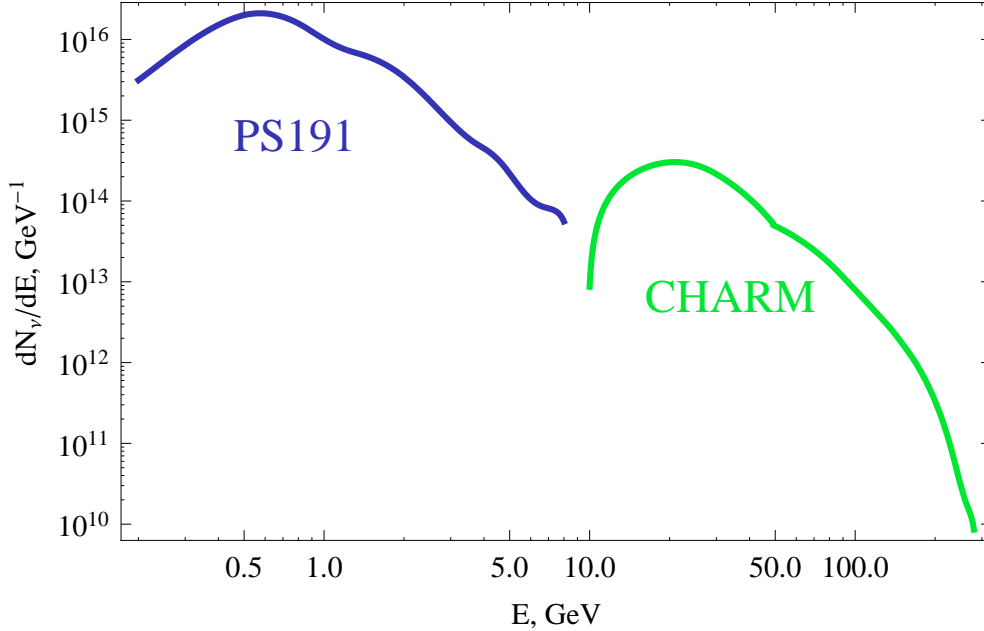


Figure 1: Neutrino spectra in CERN PS191 and CHARM experiments.

of process (2), neutrino loses about three-quarters of its energy in each emission [3], so even for $E \sim 200$ MeV the energy of leptons is well above the ionization threshold of the detector, and the efficiency of registration was close to 100% [8].

For the vacuum camera of length $l \approx 10$ m each neutrino has a probability of e^+e^- -pair production

$$P = P(E) = l \cdot \Gamma \approx 0.8 \times 10^{-13} \times \left(\frac{\delta}{10^{-5}} \right)^3 \left(\frac{E}{1 \text{ GeV}} \right)^5 . \quad (6)$$

For a given neutrino energy interval one writes for the number of e^+e^- -pairs from nothing:

$$N = \int dE \frac{dN_\nu}{dE} P(E) . \quad (7)$$

In the original search for sterile neutrino [7] the obtained limit was based on a set of requirements on the signal events, one of which is the absence of any double track events due to the e^+e^- pair. In our case the angle between electron and positron is small, $\sim \sqrt{\delta}$, well below the detector angular resolution, $\sim 10^{-2}$, see Fig. 2. To constrain neutrino superluminality we use the subset DST2 of ~ 4000 events which (judging on description presented in Ref. [9])

includes our signal events (if any): one expects a single track with double heat in electromagnetic calorimeter. Having no real data in hand, we cannot proceed further in analysis of DST2. Then, to obtain the limit on δ , we do not subtract SM background and suppose that all these ~ 4000 are due to the Cohen-Glashow effect. One can set an upper limit on δ at 95% C.L. by adopting the normal distribution and requiring $N \lesssim 4100$. Then for the energy-independent δ we integrate in r.h.s. of Eq. (7) over the entire interval of neutrino energies 0.2–8 GeV and obtain

$$\delta < 2.2 \times 10^{-6} \text{ at 95\% CL .}$$

In the case of energy-dependent $\delta = \delta(E)$ one has to integrate in r.h.s. of Eq. (7) to obtain the limits on neutrino dispersion relation. In particular, if $\delta(E)$ does not vary significantly in the energy interval $E \pm E/2$, one can exploit the relation

$$4100 \gtrsim N_E \equiv \int_{E-E/2}^{E+E/2} dE' \frac{dN_\nu}{dE'} P(E') \approx l \delta^3(E) k' \frac{G_F^2}{192 \pi^3} \int_{E-E/2}^{E+E/2} dE' \frac{dN_\nu}{dE'} E'^5$$

to set a limit on moderately-varying $\delta(E)$ as presented in Fig. 2.

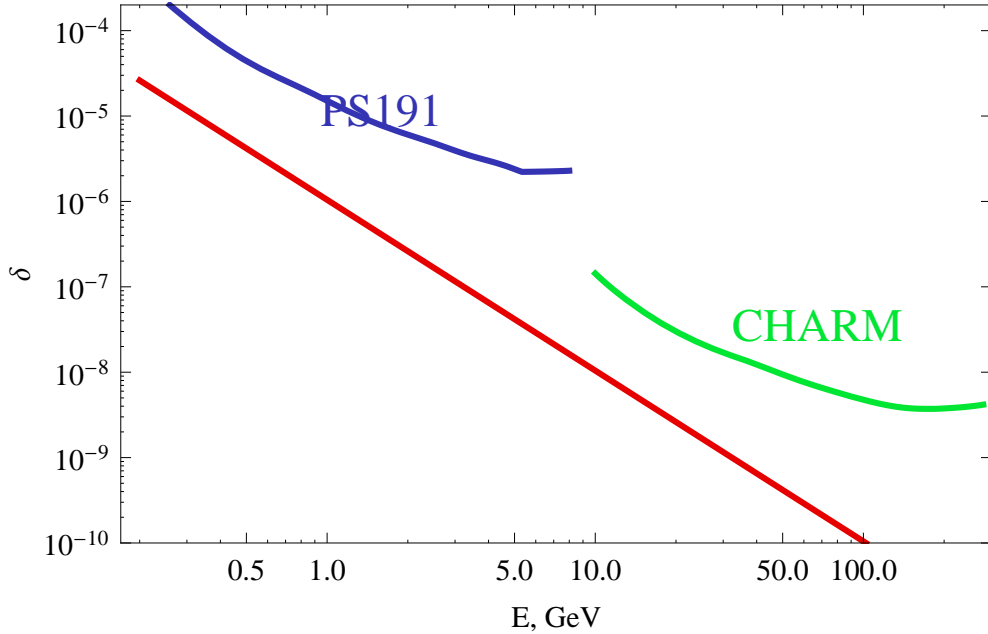


Figure 2: Upper limits on $\delta(E)$ from the results of CERN PS191 and CHARM experiments; straight line refers to the pair-production threshold (5), so the region below this line is kinematically forbidden.

We obtain similar limits from the negative results of CHARM experiment [10] which also performed searches for sterile neutrino decays. In this experiment, the CHARM detector of length $l \approx 12$ m was exposed to wide-band neutrino beam produced by $\sim 1.4 \times 10^{18}$ protons with energies ~ 400 GeV incident on a copper target. The neutrino spectrum expected from Monte Carlo simulations¹ is given in Ref. [11] and shown in Fig. 1. The selected events were required to have a shower energy W deposited in the CHARM calorimeter between 7.5 and 50 GeV and a value of the variable $W^2\theta^2$ below 0.54 GeV^2 (θ is the angle between the shower axis and the direction of incoming neutrino). A total of 331 events were selected. The number of events attributed to heavy neutrino decay is compatible with zero, 1 ± 41 event. In the case of decay (2) one has $\theta^2 \sim \delta$, so the selected above cuts do not interfere in our analysis. To place a limit on δ in this case we require to have less than 85 events due to the bremsstrahlung (2). Also, the statistics for e^+e^- production from nothing was approximately doubled when detector was exposed to muon antineutrino flux produced by $\sim 5.7 \times 10^{18}$ protons on target [10]. For energy-independent δ we obtain from (7) after integrating over the whole available neutrino energy range 10–280 GeV, and taking into account the 44% efficiency [10] of e^+e^- -registration,

$$\delta < 3.6 \times 10^{-9}.$$

This limit is stronger than the constraint (3) obtained by the ICARUS collaboration. Strikingly, this limit is even comparable to the stringent direct bound [12] obtained from the observations [13] of neutrino signal from Supernova 1987a,

$$\delta < 4 \cdot 10^{-9},$$

which is valid for the energy range around 10 MeV. However, our limit is weaker than what is expected [3] from the analysis of 10-100 TeV neutrino events measured by the IceCube experiment. The reason is the strong dependence of the emission rate (4) on neutrino energy.

For a moderately-varying $\delta(E)$ we follow the procedure used for PS191 and obtain limits presented in Fig. 2.

To summarize, in this paper we have interpreted the negative results of searches for sterile neutrino decays in CERN PS191 and CHARM experiments as the restriction on e^+e^- -pair production by possibly superluminal muon neutrinos. We have set the upper limits on neutrino velocity in the energy ranges 0.2–8 GeV and 10–280 GeV supposing neutrino velocity

¹We use wide-band neutrino beam spectrum presented in [11] for CDHS detector, which was placed right in front of the CHARM detector along the neutrino beam. The effective areas of these detectors were almost identical. We thank A. Rozanov for this suggestion.

to be only moderately varying with energy. In a particular model the limit can be refined by convolution of neutrino production rate with neutrino beam spectra according to formulas presented in the paper. Covering the gap between 8 and 10 GeV should be possible with information on high energy end of the neutrino spectrum in CERN PS191 experiment. In both experiments further strengthening of the bound might be possible with adjustment of the selected cuts. In particular with lower cut on $W^2\theta^2$ in CHARM experiment. Potentially interesting limits one can expect from reanalysis of data collected at 35-meter length detector with CHARM calorimeter module installed, which was designed to search for heavy neutrinos produced by charmed meson decays [10].

Analogous limits are expected to be obtained by the dedicated analysis of the data from NOMAD experiment, see Ref. [14] for the preliminary bound.

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